IMPACT GRINDING OF SORGHUM GRAIN

by

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INTRODUCTION

The Kansas Industrial Development Commission has sponsored research projects at Kansas State College in order to more fully utilize sorghum grains. This thesis covers one phase of that work.

Sorghums have been found to be well adapted to climatic and other growth factors found in the state of Kansas, and are particularly desirable because of their drought-resistant qualities. Sorghum grains may be processed to obtain starch, wax, oil, and by-product livestock feed. Originally the starch was obtained by methods quite similar to those used in the cornstarch industry (1). The whole grain was steeped and ground. A flotation separation of the starch-bearing endosperm from the bran and germ was used. A slurry of the finely ground endosperm was tabled to produce commercially acceptable starch.

A more recent process developed in the Chemistry Department of Kansas State College under the direction of Dr. H. N. Barham is as follows: The whole grain is debranned by abrasion and aspiration. The debranned grain is then cracked by a single stage impact grinder. The product from this grinder is screened; the portion retained on a ten-mesh screen is returned to be recracked. That portion of the cracked grain which is retained on a 30-mesh screen and under a 10-mesh screen is aspirated to remove any remaining bran which is loosed in the cracking operation. An Oliver gravity separator is used to separate the endosperm particles

from the impure germ. The endosperm is then steeped and finely wet ground by a buhr mill. The resultant slurry is screened and washed to remove the greater part of the fibrous protein-containing gluten. The underflow and washings from the screens are tabled to produce starch.

Methods of grinding the whole or debranned grain which exert a compressing or shearing action on the grain are undesirable because oil is expressed from the germ. Germ, or pieces of germ, are objectionable in the endosperm fraction since they contain considerable amounts of oil which is released during the fine grinding in the buhr mill. Such contamination of the endosperm by germ oil causes rancidity in the resultant starch. Impact grinding tends to eliminate this disadvantage. An ideal impact grinder would crack the debranned grain into several pieces, splitting out the whole germ and producing no extremely fine particles.

THE THEORY OF IMPACT GRINDING

Impact grinders can be classified into three groups with reference to the number of impacts received by the material as it passes through the machine.

1. Single-Stage grinders. In this type of machine the material is given sufficient velocity so that, upon striking a stationary surface, breakage or crushing occurs. The only impact received by the material occurs when it strikes the stationary surface. Velocity may be imparted to the material by revolving impellers or other mechanical means, or by air, steam, or other fluids.

2. Two-Stage grinders. The working parts of this type of machine are a set of revolving beaters or impactors and a stationary surface. The material receives impact upon contact with the surfaces of both working parts. The hammer mill is an example of this type of machine, in which the stationary surface is a screen which retains the material within the impact zone until it is reduced sufficiently to pass through the openings of the screen. This process produces a mixture of fine bran, endosperm, and germ, the separation and classification of which is practically impossible.

3. Multi-Stage grinders. These machines have alternate concentric rings of rotating and stationary impactors. After the material is subjected to several impacts, it is rejected from the machine and purified before receiving additional reduction.

The single stage impact grinder was investigated as a means of cracking debranned sorghum grain as one of the steps in the process of producing starch. The possibility of using compressed air to accelerate the grain was discarded because of the large power requirements and operational difficulties. In the machine used, the velocity was imparted to the grain by a revolving impeller wheel.

Grain fed into the center of an impeller wheel of radius, r, revolving with an angular velocity, ω, will leave the periphery of the wheel with a velocity, v. Velocity is a function of ω, r and the force of friction which opposes the motion of the grain. The velocity, v, can be resolved into the two com-

ponents, tangential velocity, v_t, and normal velocity, v_n.

Angular velocity, ω, is the time rate of angular motion, and when it is constant may be described by

$$\omega = \theta/t$$

where θ is the angle in radians swept through in time, t(2). In circular measure the angle is the ratio of the length of the arc, s, to the radius, r,

$$\theta = s/r$$

therefore

$$\omega = s/rt$$

But the linear velocity of a point of distance, r, from the axis is

$$v_t = s/t$$

hence

$$v_t = \omega r \qquad (1)$$

Neglecting friction, the normal force acting on the grain is given by

$$F = mv_t^2/r = m\,\omega^2 r$$

where m is the mass of the particle of grain. Since acceleration is F/m, the normal acceleration is $\omega^2 r$. From the equations for acceleration and velocity,

$$a_n = dv_n/dt \quad \text{and} \quad v_n = dr/dt$$

it is seen that

$$a_n dr = v_n dv_n$$

From this relationship

$$\int_o^r a_n dr = \int_o^{v_n} v_n dv_n = \int_o^r \omega^2 r dr$$

These limits used above assume that the grain falls into the center of the impeller wheel and at that time has no normal velocity. Integration gives the following equation relating the normal component of velocity to angular velocity and the radius of the impeller wheel:

$$v_n = \omega r \tag{2}$$

Since the tangential and normal components of velocity are equal, if the force of friction is negligible, the path of flight of the grain as it leaves the impeller wheel makes an angle of forty-five degrees with the tangent to the wheel at its point of last contact.

Adding the two components of the velocity, the actual velocity, v, is given by:

$$v = \sqrt{v_t^2 + v_n^2}$$

Since the tangential and normal components of velocity are both equal to r:

$$v = \sqrt{2\omega^2 r^2} \tag{3}$$

By virtue of its velocity the grain of mass, m, posses kinetic energy, KE.

$$KE = \tfrac{1}{2}mv^2 = m\omega^2 r^2 \tag{4}$$

Because of the inelastic impact, the kinetic energy of the grain is partially converted into the work necessary to crack the grain when it strikes the stationary casing. Thus the loss in kinetic energy is seen to be a function of the cracking produced, provided the force is great enough to exceed the elastic limit of the grain.

EQUIPMENT

The impact mill used, consisting of an impact grinder, a collection box, a blower, and a cyclone separator, is shown in Fig. 1. The impact grinder was powered by a vertically mounted, series wound motor capable of developing a speed of 4200 RPM. The impeller wheel of cast aluminum was five and seven-eights inches in diameter with four radial slots one-half inch deep, three-sixteenths inches wide at the periphery, and seven-sixteenth inches wide where they join the one-inch square center hole. A grain storage hopper with a variable flow valve was placed above a funnel which fed the grain into the center of the impeller wheel. Enclosing the impeller wheel was a removable casing, on which the grain impinged, a sheet metal cover above, and a cracked grain collection manifold below. The grain was conducted through a cylindrical sheet metal spout to a wooden collection box. This collection box was fitted with two interchangeable drawers. A blower installed in the line between the collection box and the cyclone separator produced a negative pressure in the collection box to eliminate leaks and also blew any very fine material into the cyclone separator. Two air jets were installed in the system to supplement the action of the blower.

Most of the grinding data were taken using a cylindrical sheet metal casing. Some subsequent data were taken using the cast aluminum corrugated casing shown in Fig. 2.

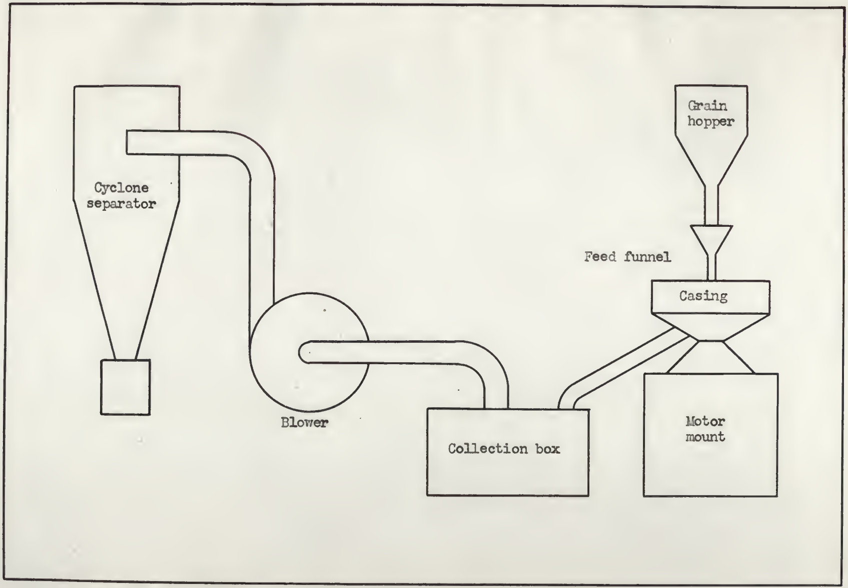

Fig. 1. Flow sheet of impact grinding process.

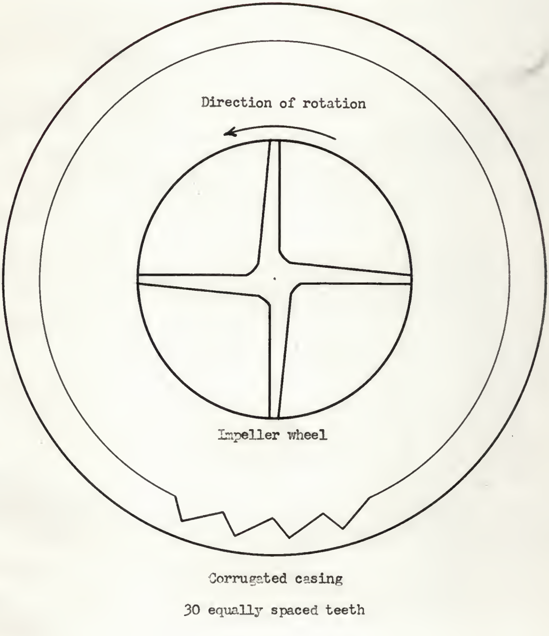

Fig. 2. Impeller wheel and corrugated casing.

A commercial sample splitter with 24 3/8-inch slots, alternate slots discharging on opposite sides, was used to obtain small representative samples of cracked grain.

Eight-inch U. S. standard testing sieves Numbers 10, 16, 20, and 30 were used to make the sieve analyses. A sieve shaker was used to insure uniform results. This shaker consisted of a sieve holder suspended on a framework. The sieve holder was vibrated by the rotation of an off-center bolt on a flexible shaft drive.

A stroboscopic tachometer was used to determine the speed of the impeller wheel. A 100-ohm rheostat and a 16-ohm variable resistance were used to regulate the speed of the motor.

A wattmeter, a voltmeter, and an ammeter were used to measure the power input to the motor. The ammeter and the current coil of the wattmeter were connected in series with the motor. The voltmeter was placed in parallel with the motor and on the power side of the ammeter. The wattmeter potential coil had a resistance of 7320 ohms, and was placed in parallel with the load and on the power side of the current coil of the wattmeter.

In increasing the moisture content of the grain a rotary drum mixer was used. A five-kilogram balance, graduated in g, and a 125-pound scales, graduated in ounces, were used in determining various weights. A vacuum drying oven and an analytical balance were used in the determination of the moisture content of the grain samples.

PROCEDURE

All sorghum grain employed in this work was of the variety called Westland Milo. It was grown in Grant County, Kansas, near Ulysses and harvested in 1946. It was delivered to the Chemical Engineering Department of Kansas State College in November, 1946. After cleaning, it was stored in a Webster sheet metal granary. Prior to grinding, the grain was debranned by abrasion and aspiration. To remove any grain cracked in the debranning operation, the debranned grain was screened, and that portion which was retained on a ten-mesh screen was used. The following general procedure was used for all runs.

Eight or 10 pounds of grain were placed in the storage hopper of the impact grinder. The blower and air jets were turned on. The motor was turned on and the speed adjusted to some predetermined value by varying the resistance. Most runs were made at 2500, 3000, 3500, and 4000 RPM. The wattmeter, ammeter, and voltmeter values were noted and recorded. The flow valve was opened to admit grain into the grinder at a previously calibrated rate. As grinding commenced, the variable resistance was adjusted to keep the motor speed constant. During the grinding at a known feed rate and RPM, the wattmeter, voltmeter, and ammeter were reread and recorded. At the conclusion of the grinding, the motor was turned off and any cracked grain remaining in the collection manifold was brushed down the spout into the collection box. The blower and the air jets were then turned off. The contents of the collection box drawer and the fine

material in the cyclone separator were removed and run through the sample splitter to obtain a one-pound-sample. This sample was then placed in the sieves and shaken for 15 minutes. The amount of cracked grain retained on each sieve and the amount passed through the Number 30 sieve were then determined by weighing on the five-kilogram balance.

In order to study the effect of moisture content and tempering process on the grindability of the grain, a number of different procedures were used. For instance, in one series of runs the debranned whole grain, moisture content approximately 11 percent, had varying amounts of water mixed with it for 10 minutes immediately preceding cracking. In another series, the grain had varying amounts of water added, and was then held at 160° F. for four hours. In the discussion of this phase of experimentation, the different tempering processes will be enumerated along with the results.

The moisture determination of grain was made as follows. The sample was weighed on an analytical balance. Next it was dried in a vacuum oven at 110° C. and 29 inches of mercury vacuum for two hours. After cooling in a desiccator, the sample was reweighed.

Before replacing the cylindrical sheet metal casing with the cast aluminum corrugated casing, a three-sixteenths inch vertical slot was cut into the sheet metal casing in order to determine the angle at which the grain left the impeller wheel.

DATA

The experimental data collected fall into three main categories:

(1) Grinding of debranned whole grain at different feed rates and impeller wheel speeds using a cylindrical sheet metal casing.

(2) Grinding of debranned whole grain using different tempering procedures and the cylindrical sheet metal casing.

(3) Grinding of debranned whole grain and of grain which had been previously ground but which was larger than the openings of a Number 10 screen, employing a cast aluminum corrugated casing.

The data taken on the runs at different feed rates and impeller wheel speeds are presented in Table 1. Five different feed rates, varying from 2.7 to 9.1 pounds per minute, were investigated. The range over which the impeller wheel speeds were varied was 1850 to 4200 RPM. The grain used in this series received no tempering treatment and was ground with a natural moisture content of 11 percent (dry basis).

The data showing the results obtained by different tempering procedures are given in Tables 2 and 3. For these runs the grinding was performed at 3500 RPM. The feed rate was approximately 4.3 pounds per minute. For a constant setting of the feed flow valve the feed rate for grain with a relatively high moisture content was slightly less than the feed rate for the

Table 1. Data on impact grinding of debranned whole grain as received.

Run	RPM	K.E. of grain, ft.-lbs. per lb.	Power, Watts per lb. per minute	Percent between No.10 & 30 sieve	Percent through a No.30 sieve	Fineness Modulus
		Feed rate: 2.7 pounds per minute				
101	2500	128	2.7	8.5	0.7	3.87
102	3000	184	4.1	26.2	1.4	3.65
103	3500	250	9.7	30.5	2.4	3.55
104	4200	356	21.8	51.5	4.5	3.20
		Feed rate: 4.3 pounds per minute				
111	1850	70	2.4	4.0	0.1	3.95
112	2600	138	4.4	15.6	0.7	3.80
113	3000	184	2.8	31.6	1.7	3.58
114	3500	250	8.4	36.8	2.9	3.47
115	4000	326	11.4	53.8	4.1	3.19
		Feed rate: 4.9 pounds per minute				
121	3250	215	4.9	39.0	1.6	3.48
122	3500	250	8.8	46.7	3.0	3.33
123	3750	285	9.7	48.7	3.1	3.29
		Feed rate: 5.7 pounds per minute				
131	2500	128	4.5	10.6	0.9	3.85
132	3000	184	7.7	26.4	1.8	3.62
133	3500	250	12.6	31.0	2.4	3.61
134	4000	326	14.4	51.0	3.9	3.25
		Feed rate: 9.1 pounds per minute				
141	2500	128	5.3	8.4	0.7	3.86
142	3000	184	5.5	9.9	1.2	3.84
143	3500	250	8.0	25.3	1.7	3.65
144	4000	326	10.3	35.3	2.8	3.49

Table 2. The effect of increasing the moisture content of grain on its grindability.

Run	% Moisture, dry basis	Percent between No. 10 & 30 sieve	Percent through a No. 30 sieve
The debranned, whole grain was mixed with water for five minutes prior to grinding at 3500 RPM			
201	11	43.7	2.2
202	14	33.9	2.0
203	16	28.0	2.0
204	19	35.4	1.1
The debranned, whole grain was held at 160° F. for sixteen hours and then mixed with water for ten minutes prior to grinding at 3500 RPM			
211	11	33.3	2.2
212	17	21.3	0.9
213	21	20.8	1.2
214	23	23.9	1.6
215	26	19.3	1.5
The debranned, whole grain was mixed with water for ten minutes and was then held for four hours at 160° F. prior to grinding at 3500 RPM			
221	11	38.4	2.2
222	14	29.3	2.0
223	21	26.7	1.8
224	26	22.9	1.1

Table 3. The effect of decreasing the moisture content of grain on its grindability.

Run	Drying time minutes	Percent between No. 10 & 30 sieve	Percent through a No. 30 sieve	Fineness modulus
The debranned whole grain was dried in a rotary drum drier at 155° F. prior to cracking at 3500 RPM				
301	10	43.4	2.8	3.39
302	30	43.8	2.8	3.38
The whole grain had its overall moisture content increased to eighteen percent (dry-basis) before debranning and was then dried in a rotary drum drier at 155° F. prior to cracking at 3500 RPM				
311	45	35.1	2.1	3.51
312	90	47.8	1.9	3.37

Table 4. Data obtained using corrugated casing.

Run	RPM	Percent between No. 10 & 30 sieve	Percent through No. 30 sieve	Feed Rate lbs. per minute	Fineness modulus
Data on debranned whole grain					
401	3100	43.1	2.2	4.8	3.42
402	3500	45.9	2.8	4.8	3.35
Data on partially cracked grain					
411	3100	51.7	2.3	5.0	3.30
412	3500	56.2	3.3	5.0	3.21

drier grain. In Table 2 the data for the first run of each series are from grain whose original moisture content of 11 percent was unaltered, although the grain was subjected to the tempering procedure as indicated.

Table 4 gives the data obtained using a cast aluminum corrugated casing. The grain used for runs 401 and 411 had received no tempering treatment, and was ground at an impeller wheel speed of 3100 RPM. For run 401, debranned whole grain was used, and 45.3 percent of it was ground smaller than the opening of a Number 10 sieve. The grain used for run 411 was 45.3 percent debranned whole grain, and 54.7 percent was grain which had been cracked previously but was larger than the openings of a Number 10 sieve. Runs 402 and 412 were similar to runs 401 and 411 except that they were made at an impeller wheel speed of 3500 RPM.

The angle between the path of flight of the grain and the tangent to the impeller wheel at the point of last contact were measured at different impeller wheel speeds ranging from 2500 to 4000 RPM, and was found to be approximately constant at forty-four degrees.

DISCUSSION

The results of grinding debranned whole grain at different feed rates and impeller wheel speeds are presented in Table 1. The kinetic energy of the grain was calculated by equation (4), and represents the foot-pounds of energy possessed by one pound of grain.

The power tabulated in column four of Table 1 was calculated as follows: The wattmeter readings were corrected by subtracting the power consumed by the meter. This power is equal to the square of the voltage across the potential coil divided by the resistance of the potential coil. From these corrected wattmeter readings was subtracted that part of the stray power losses represented by the product of the resistance of the motor circuit and the square of the current through it. The power value thus obtained from measurements at a particular motor speed and with no grinding load was subtracted from the power value at the same motor speed but with a grinding load. This difference, divided by the feed rate, represents the power in watts consumed by the motor in grinding one pound of grain per minute.

The fineness modulus reported in Table 1 is the sum of the percentages by weight coarser than each sieve divided by one hundred. The average particle diameter is related to the fineness modulus by the equation:

$$\text{Fineness modulus} = \frac{\ln\left(\frac{d\sqrt{x}}{y}\right)}{\ln x}$$

where d is the average diameter, x is the ratio of openings for consecutive sieves, and y is the width of opening of the finest sieve.

The relationship between the grinding effected and the kinetic energy of the grain are illustrated in Figs. 3, 4, 5, and 6 for the several feed rates employed. For each feed rate the percent of cracked grain (that which passed through a Number 10 sieve and was retained on a Number 30) and the percent of flour

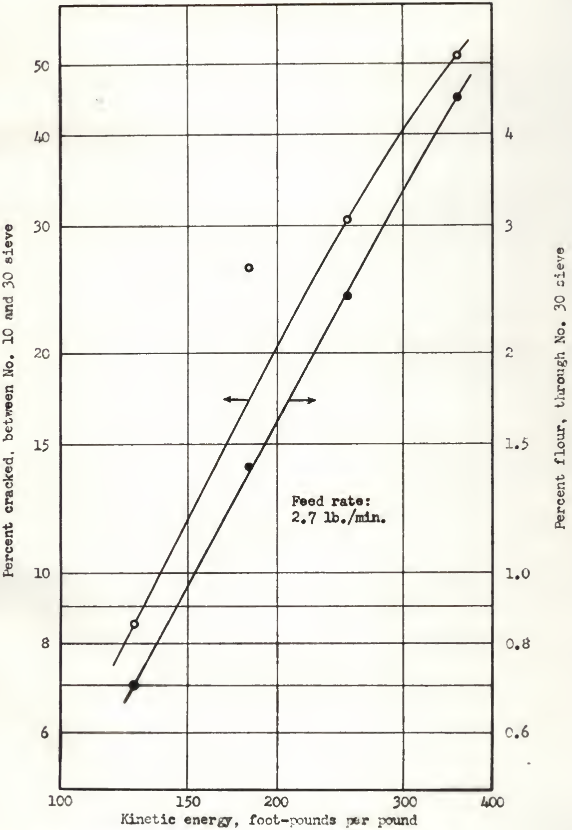

Fig. 3. Kinetic energy vs. percent cracked and percent flour.

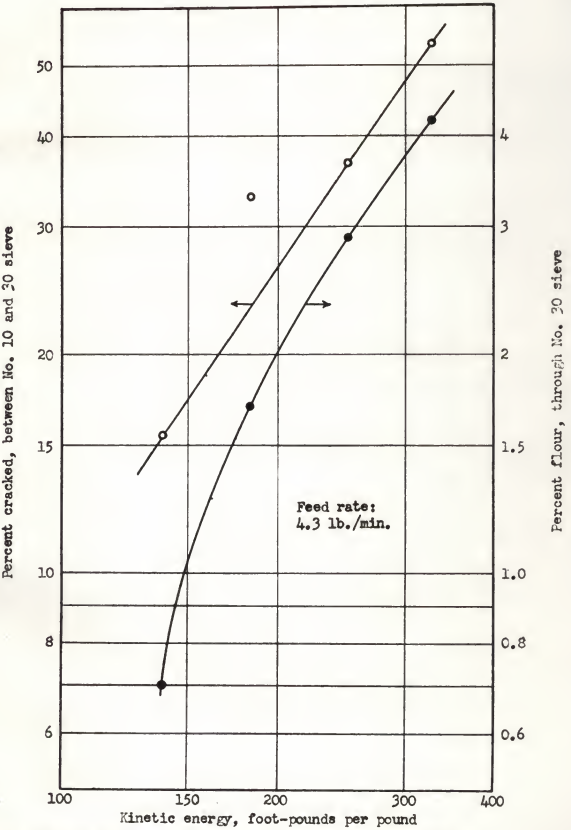

Fig. 4. Kinetic energy vs. percent cracked and percent flour.

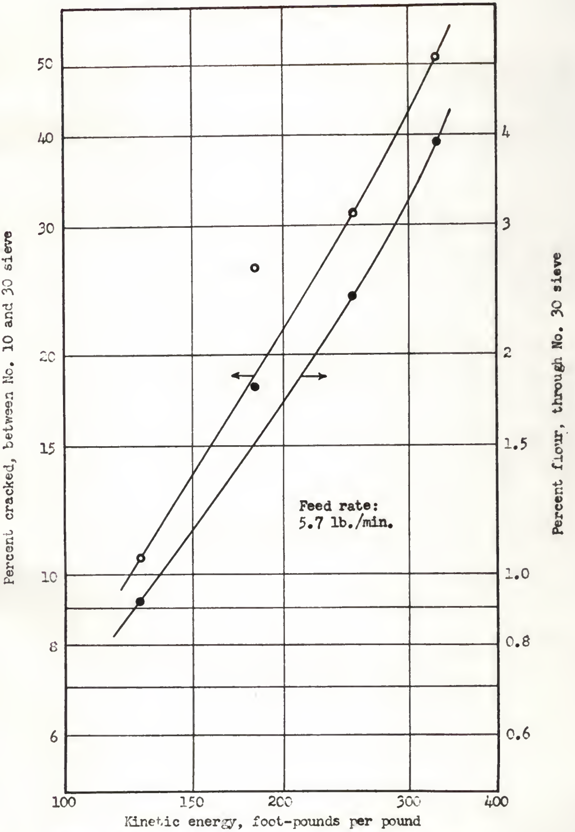

Fig. 5. Kinetic energy vs. percent cracked and percent flour.

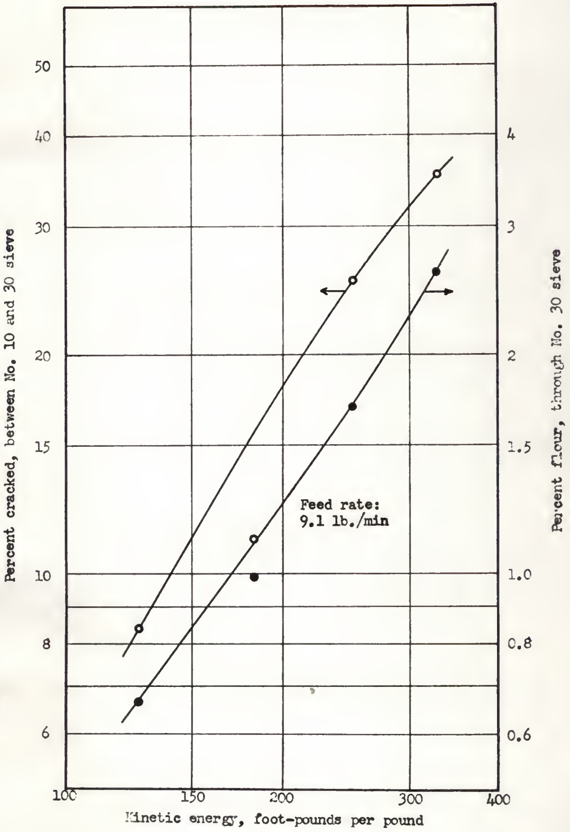

Fig. 6. Kinetic energy vs. percent cracked and percent flour.

(the material finer than a Number 30 sieve) are plotted versus kinetic energy on logarithmic scales. The points fall on a smooth curve except for some of the values at a kinetic energy of 184 foot-pounds per pound, corresponding to an impeller wheel speed of 3000 RPM. It was not determined whether this treatment of the data or the accuracy of the data was the cause of this discrepancy. Logarithmic scales were used in order to best present the data and to show that the percent cracked and the percent flour produced both may be expressed as functions of the kinetic energy raised to some exponent. For the different feed rates this exponent varied from 1.46 to 1.82 with an average value of 1.61 and with an average deviation of 7.5 percent from the average.

The relationship of the amount cracked and flour produced at much higher kinetic energy values could not be investigated with the impeller wheel size employed because the speed was limited to a maximum of 4200 RPM. It may also be noted that, for any kinetic energy values, the percent of grain cracked is 12 to 15 times greater than the percent of flour produced.

The effect of varying the feed rate is presented in Fig. 7. The curves of percent cracked and percent flour produced versus the feed rate shown are for an impeller wheel speed of 3500 RPM. At other impeller wheel speeds, similar curves were obtained with maximums at the same feed rate values of 4.9 pounds per minute.

Two main theories concerning the power consumed in crushing operations have been advanced; however, no theories specifically

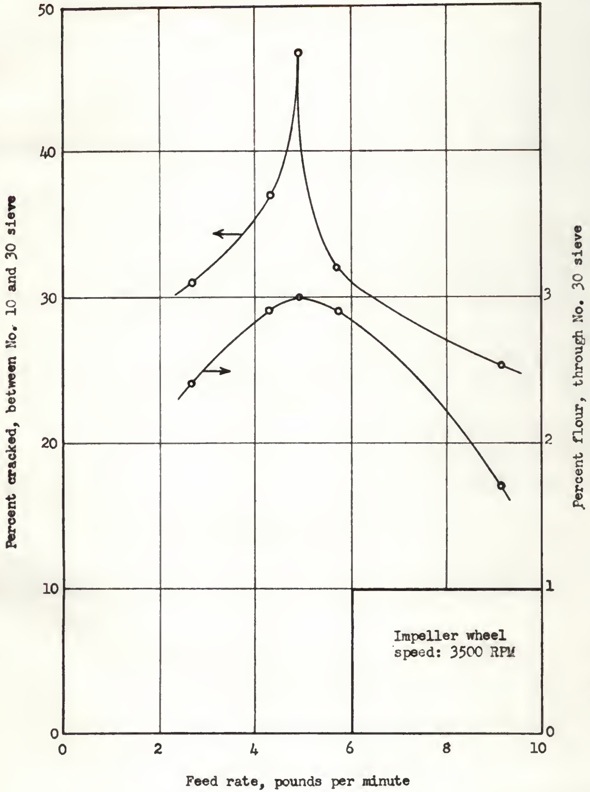

Fig. 7. The effect of feed rate on cracking at 3500 RPM.

related to the power consumption of the impact grinder have been presented. Kick's law assumes that the energy required for grinding is proportional to the logarithm of the ratio between the initial and final diameters. The law of crushing proposed by Rittinger was based on the assumption that the energy requirement is proportional to the new surface formed. Rittinger's law is best expressed thus,

$$P = C(1/d - 1/D)$$

where P is the power required to grind the material at a given rate, C is an arbitrary constant depending on the type of grinder and material ground, D is the average particle diameter of the feed, and d is the average particle diameters of the product. These laws have a theoretical background, but neither exactly expresses the performance of any actual grinding machine (3).

The applicability of these crushing laws to the data obtained was determined. A plot of power, expressed as watts required to grind grain at a rate of one pound per minute, versus D/d on semi-logarithmic coordinate paper is depicted in Fig. 8. The average diameter of the debranned whole grain was determined by a sieve analysis using sieves Number 7, 8, and 10. No grain was retained on the Number 7 sieve, 47 percent was retained on the Number 8 sieve, and 53 percent was retained on the Number 10 sieve. Assuming that the average diameter of the grain between two consecutive sieves is equal to the average of the width opening of the two screens, the average diameter of the debranned whole grain was found to be 0.093 inch. The average particle diameter of the cracked grain was determined from the fineness

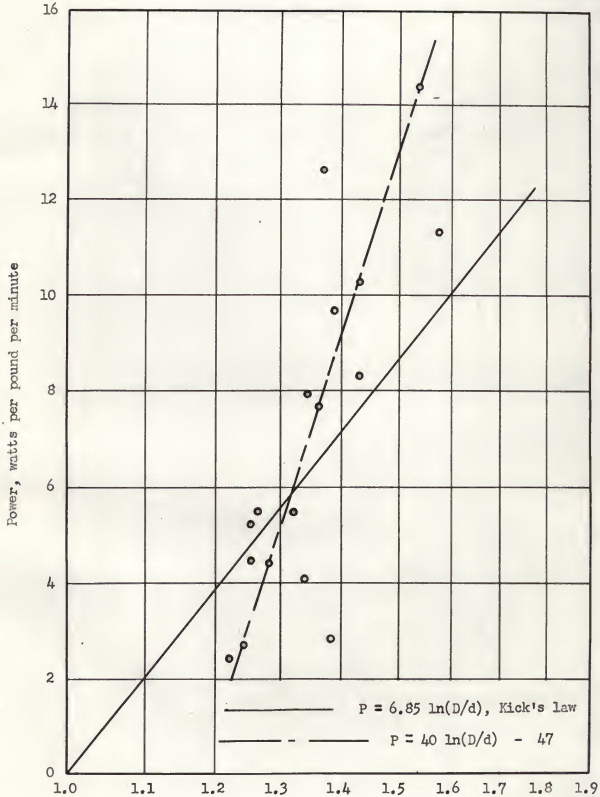

Fig. 8. The application of Kick's law.

modulus as described above.

The curve illustrating the application of Kick's law (Fig. 8) was drawn through the point representing zero power and no size reduction with a slope equal to the average of the values obtained by dividing power values by their corresponding ln D/d values. The equation of this curve is

$$P = 6.85 \ln(D/d)$$

and it is seen to represent the actual relationship only in a small range. The dashed curve whose equation is

$$P = 40 \ln(D/d) - 47$$

more accurately represents the data.

The application of Rittinger's crushing law, to the same data as was used in Fig. 8, is presented in Fig. 9. The curve representing Rittinger's law was drawn through the origin with a slope equal to the average of the values obtained by dividing each power value by its corresponding $(1/d - 1/D)$ value. The equation of this curve is

$$P = 1.94\ (1/d - 1/D)$$

but the dashed curve on Fig. 9 more accurately represents the data. It should be noted that when the dashed curve on Figs. 8 and 9, which represent the data in the range investigated, are extended to zero power, they both indicate that size reduction could be accomplished without power.

In the investigation of the effect of different tempering procedures on the grindability of grain, two series of runs were performed. In the first series, the moisture content of the grain was increased,and the results are shown in Table 2. The

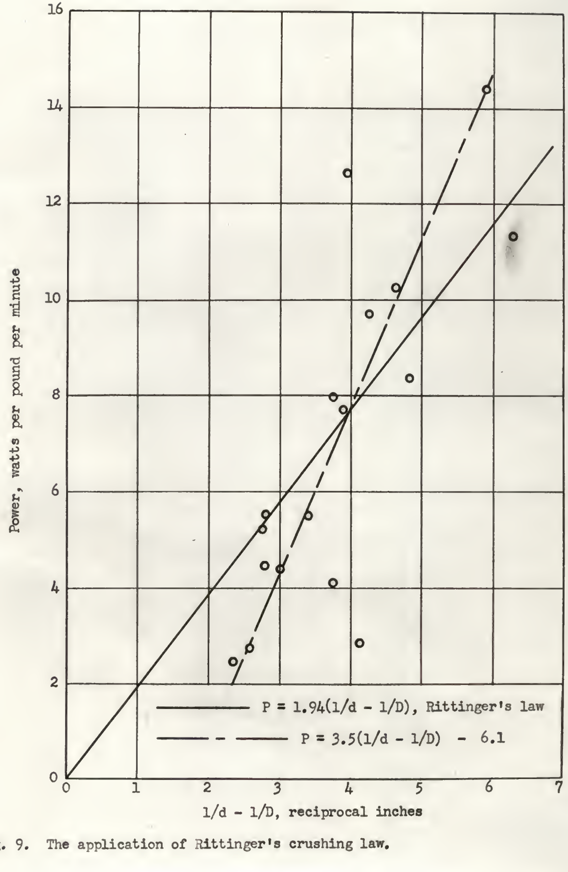

Fig. 9. The application of Rittinger's crushing law.

second series involving the drying of the grain is shown in Table 3. In general, decreasing the moisture content of the grain seemed to make the grain harder and more brittle, and improved its grindability. Conversely, increasing the moisture content of the grain seemed to make it tougher, more resilient, and impair the grindability, although it resulted in the production of a smaller percent of flour. In both series the feed rate was approximately 4.3 pounds per minute, and the impeller wheel speed was 3500 RPM.

In the sequence of runs numbered from 201 to 204, the debranned whole grain had water added to bring the moisture content up to the value indicated, and was agitated in a rotary drum mixer for five minutes immediately preceding grinding. The percent cracked decreased markedly as the moisture content was increased to 16 percent and then increased slightly at 19 percent.

For runs 211 through 215, the whole grain was held at 160° F. for 16 hours and was then mixed with enough water for 10 minutes to obtain the moisture content indicated. The percent cracked at each moisture level was considerably less than that obtained at corresponding moisture contents without the heat treatment. For this sequence, the percent cracked decreased steadily as the moisture content was increased, except run 214, having a moisture content of 23 percent, which was slightly high. This slight increase at that moisture level was also observed in the first sequence of this series; viz., run 204.

The effect produced by heating grain of different moisture contents at 160° F. for four hours before grinding was similar

to the previous two treatments. The percent cracked for each moisture level was between the values obtained by the other two procedures.

In the series performed to investigate the effect of decreasing the moisture content of grain on its grindability, the grain was dried in a small countercurrent rotary drum drier at 155° F. The results obtained with no drying, drying for 10 minutes, and drying for 30 minutes were all essentially the same, except that the drying produced a larger percent of flour.

Before this experiment was completed it was found that wetting the whole grain improved the debranning operation. The debranning procedure decided upon consisted of increasing the overall moisture content of the grain to 18 percent. The debranning operation was completed before the moisture penetrated into the center of the grain, and, therefore, the moisture content was reduced by debranning. The time interval from the addition of the water to placing the grain in the drier was 40 minutes. The grain used in runs 311 and 312 was debranned by this process. Run 311 was dried at 155° F. for 45 minutes, and the percent cracked indicated that the moisture content was probably slightly above 11 percent. A similar run, Number 312, was dried for 90 minutes at the same temperature and 47.8 percent was cracked, which is greater than that obtained by any other procedure. Also the amount of flour produced was relatively small. The wetting and subsequent drying in this procedure seem to produce microscopic cracks in the grain and make it hard and more easily cracked.

In determining the direction of the path of flight of the grain as it left the impeller wheel, a three-sixteenths inch vertical slot was cut in the cylindrical sheet metal casing. It was found that a considerable quantity of cracked grain flew out of this slot in a fan-shaped pattern, which made it difficult to ascertain the path of the whole grain. The velocity of the whole grain through the slot was considerably greater than that of the cracked grain. A target, consisting of a large piece of pencil carbon paper covering a sheet of white paper upon which the grain impacts were registered, was placed at a distance of 88 inches from the slot. The angle formed by the intersection, at 88 inches from the slot, of the grain flight path and the radial line from the center of the impeller wheel was found to be approximately 1.3 degrees for impeller wheel speeds of 2500, 3000, 3500, and 4000 RPM. From this data, the angle between the path of flight of the grain and the tangent to the impeller wheel at the point of last contact were found to be 44 degrees. The fact that this angle was so close to 45 degrees indicated that the retarding friction force was small and that the tangential and normal components of the grain's velocity as it left the impeller wheel were nearly equal.

Because of the diameters of the impeller wheel and the casing, the grain struck the casing at an angle of approximately 25 degrees from the normal. On the assumption that more cracking would be affected if the grain hit the casing at right angles to its path of flight, the corrugated casing shown in Fig. 2 was designed by the author and fabricated by the Shop Practice Depart-

ment of Kansas State College. Table 4 represents the results obtained using this casing. Runs 401 and 402 were made on debranned whole grain with impeller wheel speeds of 3100 and 3500 RPM, respectively. The results of these runs were similar to the results obtained using the cylindrical sheet metal casing at comparable feed rates and impeller wheel speeds, although the run at 3100 RPM using the corrugated casing achieved better results. Runs 411 and 412 were made on partially cracked grain, and indicate that in continuous grinding using this equipment, the feed to the grinder would consist of approximately one-half whole grain and one-half oversized cracked grain, with slight variations depending upon the feed rate and impeller wheel speed used.

The fundamental concept of single-stage impact grinding has been investigated along with its application to the grinding of sorghum grain to facilitate separation of the starch-bearing endosperm from the germ. If a sorghum grain products industry is to be developed which will compare with the now existent corn products industry, investigation into the several steps of the process should be more closely integrated. Future investigators of this subject should analyze the endosperm fraction for its oil content and determine how the cracking procedure affects it. Investigation of different impeller wheel and casing designs should be made to try to find a combination which would crack a larger percent of grain without producing an excessive amount of flour, and still produce a product whose endosperm fraction has a low enough oil content to be processed into starch.

SUMMARY

1. The impact grinding of sorghum grain produced a product which could be satisfactorily separated into a germ fraction and an endosperm fraction of sufficiently low oil content for processing into commercially acceptable starch.

2. It was found that the amount cracked and the flour produced increased with the RPM of the impeller wheel. The amount cracked and the amount of flour produced are proportional to the kinetic energy of the grain to an exponent of approximately 1.6.

3. The feed rate affects the results of impact grinding at constant impeller wheel speeds. An optimum feed rate of 4.9 pounds per minute for all impeller wheel speeds investigated was determined for the equipment used.

4. Increasing the moisture content of sorghum grain impairs its grindability.

5. A satisfactory tempering treatment was developed for improving the grindability of sorghum grain.

6. The power consumption of the impact grinder used was not accurately represented by either Kick's or Rittinger's crushing law.

7. The theoretical grain velocity as it leaves the impeller wheel was substantiated by experimentation.

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SYMBOLS USED

a	acceleration
C	arbitrary constant
D	initial average particle diameter
d	final average particle diameter
F	force
KE	kinetic energy
m	mass
P	power
r	radius
RPM	revolutions per minute
s	length of arc
v	linear velocity
θ	angle of rotation
ω	angular velocity

Subscripts

n	normal component
t	tangential component

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